Conjugate Heat Transfer Investigation on the Cooling Performance of Air Cooled Turbine Blade with Thermal Barrier Coating Postprint

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Abstract

A hot wind tunnel of annular cascade test rig is established for measuring temperature distribution on a real gas turbine blade surface with infrared camera. Besides, conjugate heat transfer numerical simulation is performed to obtain cooling efficiency distribution on both blade substrate surface and coating surface for comparison. The effect of thermal barrier coating on the overall cooling performance for blades is compared under varied mass flow rate of coolant, and spatial difference is also discussed. Results indicate that the cooling efficiency in the leading edge and trailing edge areas of the blade is the lowest. The cooling performance is not only influenced by the internal cooling structures layout inside the blade but also by the flow condition of the mainstream in the external cascade path. Thermal barrier effects of the coating vary at different regions of the blade surface, where higher internal cooling performance exists, more effective the thermal barrier will be, which means the thermal protection effect of coatings is remarkable in these regions. At the designed mass flow ratio condition, the cooling efficiency on the pressure side varies by 0.13 for the coating surface and substrate surface, while this value is 0.09 on the suction side.

Full Text

Preamble

A hot wind tunnel with an annular cascade test rig was established to measure temperature distribution on a real gas turbine blade surface using an infrared camera. Additionally, conjugate heat transfer numerical simulations were performed to obtain cooling efficiency distributions on both the blade substrate surface and coating surface for comparative analysis. The effect of thermal barrier coating on the overall cooling performance of blades was investigated under

varying coolant mass flow rates, and spatial differences were also examined. Results indicate that the cooling efficiency in the leading edge and trailing edge areas of the blade is the lowest. Cooling performance is influenced not only by the internal cooling structure layout inside the blade but also by the mainstream flow conditions in the external cascade path. The thermal barrier effects of the coating vary across different regions of the blade surface; where higher internal cooling performance exists, the thermal barrier is more effective, meaning the thermal protection effect of coatings is remarkable in these regions. At the designed mass flow ratio condition, the cooling efficiency on the pressure side varies by 0.13 between the coating surface and substrate surface, while this value is 0.09 on the suction side.

Keywords: gas turbine blade, thermal barrier coating, cooling efficiency, conjugate heat transfer

Introduction

The specific power and thermal efficiency of gas turbines improve with increasing turbine inlet temperature. However, current inlet temperatures have exceeded the limit of heat-resistant alloys. Many methods have been adopted to ensure reliable and stable operation of gas turbines in high-temperature environments. The most effective solution is to employ advanced blade materials and molding technology with better thermal performance, though this is restricted by the development of material science and manufacturing processes. In this context, advanced cooling techniques become necessary and viable options for temperature control. Additionally, thermal barrier coating (TBC) is generally applied to insulate superalloy-based blade surfaces from hot gas mainstream [1-5]. Numerous studies have investigated the cooling performance of turbine blades with different cooling structures, with and without TBC.

Boyle et al. [6] built a three-blade cascade test bench and measured temperature distribution on blade surfaces by infrared thermography at low temperature (80°C) to reveal the influences of surface roughness on cooling performance. Zhang et al. [7] measured cooling efficiency distribution on the turbine blade pressure surface with a single row of film holes for blowing ratios ranging from 1.61 to 3.02 using pressure sensitive paint (PSP) technology. Their results indicated that cooling efficiency slightly increases with blowing ratio but enhancement is not obvious. Shi et al. [8] conducted heat transfer experiments on specially designed binary cooling vanes in a three-blade hot wind tunnel test rig to study the influences of different coolant-to-mainstream parameters (temperature ratio, pressure ratio, and mass flow ratio) on temperature and cooling efficiency distribution on the vane surface. The work mentioned above does not consider the effect of the solid part on heat transfer, while it is proved to be significant. Dees et al. [9-12] investigated both adiabatic and overall cooling efficiency for gas turbine vanes experimentally and numerically under various flow and geometrical parameters, from whose results the difference between adiabatic and conjugate cases can be shown. Moreover, Kuo-San Ho et al. [13] simulated and predicted the substrate surface temperature of cooling blades with a conjugate heat transfer (CHT) model. Results showed that numerical CHT outcomes are well consistent with experimental data obtained from a full engine test with Silicon Carbide (SiC) chip measurements. Thus, previous studies on cooling performance of air-cooled blades assume the Biot number (Bi) of experimental and realistic blades to be equal, meaning similar heat transfer conditions for the solid parts. However, there is little discussion on coating thermal conduction and its thermal protection effects on cooling performance.

Coating is an important thermal barrier technology in cooled blades and has been widely applied. Therefore, clarifying the influences of thermal barrier coating on cooling performance for blades is of great importance for more accurate prediction of blade thermal behavior for designers.

Davidson et al. [14] carried out experiments to evaluate the cooling performance of turbine blades with thermal barrier coating and different film cooling structures. They pointed out that thermal barrier coating can improve cooling efficiency by 25% downstream of film holes. Heat transfer characteristics of turbine blades with ceramic thermal barrier coating were computationally assessed by Kumar et al. [15] and compared with those without coating under high temperature conditions. Results pointed out that ceramic thermal barrier coating can effectively hinder radiation heat flux to alloy blades, which is more obvious when mainstream temperature becomes higher. Tsipas [16] reported the thermophysical properties of plasma-sprayed thermal barrier coating and found that after thermal barrier coating application, the allowable temperature of the main flow can be significantly higher than the heat-resistant limit of blade material. Padture et al. [17] presented work concluding that the surface temperature of blades with TBC experienced no significant change after the mainstream temperature was increased by 70–150°C. Rossette et al. [18] numerically investigated the aerothermal performance of a first-stage gas turbine blade with TBC and internal cooling configuration, summarizing that a 100–400 µm thick coating can reduce blade substrate surface temperature by up to 200°C, meaning TBC can reduce coolant needs for blade cooling by 36% while maintaining substrate creep life. Similar work by Altun [19] also concluded a temperature decrease of 300°C due to TBC heat insulation. Another CFD work was performed by Sadowski et al. [20] to estimate the influence of coating on the thermal response of a nozzle guide vane with 0.1mm thickness layer of TBC and several cylindrical cooling channels. Results show that a 10% improvement in cooling efficiency was achieved with TBC application.

From the literature reviewed above, few investigations evaluate cooling performance of realistic air-cooled blades with complex internal cooling channels and TBC on the surface in hot gas environments. This paper uses a hot wind tunnel with annular cascade test rig to measure temperature distribution on the test blade surface with an infrared camera. Additionally, conjugate heat transfer CFD calculations were conducted to obtain cooling efficiency distribution on both blade substrate surface and coating surface for comparison after the simulation was verified by experimental results. The objective of the current work is to investigate the effect of thermal barrier coating on the overall cooling performance of blades by changing the coolant amount, and spatial differences are also discussed.

Nomenclature

Symbols: - c: specific heat capacity, J/(kg • K) - c_p: specific heat capacity at constant pressure, J/(kg • K) - l_p: absolute arc length from a point to leading edge on middle section of pressure surface, mm - T_c: inlet temperature of internal cooling channel, K - T_g: inlet temperature of cascade, K - T_s: surface temperature of blade, K - l_s: absolute arc length from a point to leading edge on middle section of suction surface, mm - x: relative arc length - L_p: absolute arc length from trailing edge to leading edge on middle section of pressure surface, mm - L_s: absolute arc length from trailing edge to leading edge on middle section of suction surface, mm - m: mass flow rate of air, kg/s - m_h: mass flow rate of main stream, kg/s - M: molar mass, kg/kmol - p: static pressure, MPa - T: temperature, K

Greek Symbols: - ρ: density, kg/m³ - η: cooling efficiency - $\bar{\eta}$: area-averaged cooling efficiency - ω: mass flow ratio - μ: dynamic viscosity, kg/(m • s) - λ: temperature ratio - κ: thermal conductivity coefficient, W/(m • K) - δ: coating thickness

Experimental Setup

The experimental system consists of a gas supply system, cooling air system, test section, and data acquisition system, as shown in Fig. 1 [Figure 1: see original paper]. In the experiment, air supplied by a 400kW blower and diesel fuel are delivered into the combustor to burn sufficiently and generate high-temperature gas. The high-temperature combustion gas then enters the plenum before flowing through the test section. Compressed air as coolant in the cooling system is provided by a piston air compressor; a pressure reducing valve and plenum are equipped to maintain steady coolant pressure. The regulating valve is manually adjusted to obtain the required cooling air amount for different operating conditions. Before distribution into the blade cooling channel, cooling air is heated by an electric heater to simulate a similar temperature ratio in real gas turbine applications.

The experimental blade is a real air-cooled gas turbine blade with two primary cooling passage chambers. The blade adopts a latticework cooling mode with different convective heat transfer enhancement structures, depicted in Fig. 2 [Figure 2: see original paper]. The front cooling chamber occupies 28% of the internal cooling region and is a normal U-shape convective cooling channel, while the rear cooling chamber occupies 28%–80% of the internal cooling region and is a latticework cooling channel with various dimple vortex generators. Regarding these two major cooling structures in this blade, Rao et al. [21] carried out mechanism adiabatic heat transfer experimental studies, and detailed structure configuration can be referred to their work. No film cooling is designed for this blade, so cooling air flows into the cooling chamber from the root and finally ejects from trailing edge slots. Additionally, the whole blade is covered with thermal barrier coating.

From the mid-span plane view, the flow inlet and outlet angles of this turbine blade are 49.5° and 20.1°, respectively, and the blade spacing is 41mm. A 7-blade annular cascade test section was built for the experiment, shown in Fig. 3 [Figure 3: see original paper]. The tunnel axis direction is consistent with the cascade inflow direction to guarantee a blade flow attack angle of 0°. The cooling air system is only assembled for the middle blade of the seven blades while the others are not cooled.

The temperature distribution on the blade external surface is measured by a VarioTHERM II infrared (IR) camera, which operates at wavelengths from 1.8 to 5.0 micrometers. The camera has a focal plane detector array of 256×256 platinum silicide detectors, with a measuring range of 268–1473K and accuracy of ±2%. The view angle is $14° \times 14°$, and spatial resolution is 1.0 mrad. Two thermocouples are installed at the inlets of the cascade and internal cooling channel to measure the hot gas and cooling air inlet temperatures. Temperature uncertainties obtained by IR camera and thermocouples are ±0.1K and ±0.5K, respectively.

Due to optical view restrictions, the IR camera cannot capture the entire blade suction surface. To detect as large a region as possible on the suction surface, two optical windows are laid out at the front and back locations of the test section cascade (see Fig. 3 [Figure 3: see original paper]). This allows the infrared camera to measure temperature distribution in the regions of 0–0.26 and 0.42–0.95 arc length of the blade suction surface. Auxiliary experiments for infrared camera calibration are conducted to obtain calibration curves for the two view spots. After calibration, infrared temperature fields can be translated into real temperature fields.

Experimental working conditions are determined based on actual turbine operation conditions in terms of mass flow ratio ω and temperature ratio λ. In the experiment, the mass flow rates of air and fuel for combustion, inflow gas temperature (733K), and temperature ratio ($\lambda = 0.53$) all remain fixed. The effect of mass flow ratio ($\omega = 0.016$–0.036) on cooling efficiency μ is investigated by changing the cooling air mass flow rate.

Data Reduction and Uncertainty Analysis

Data Reduction. The local and averaged cooling efficiency are defined as follows:

The mass flow ratio and temperature ratio are calculated based on the equations below:

And the relative arc length is described as:

Uncertainty Analysis. Experimental uncertainties are determined by standard error analysis. In this experiment, the maximum measurement error of flow rate is ±2.0% for air, and for coolant and mainstream temperature are both ±0.5K. According to the standard error analysis method suggested by Kline and McClintock [22], the errors of mass flow ratio (ω) and cooling efficiency (μ) in experimental results are ±4.0% and ±2.3%, respectively.

Numerical Modeling

Due to experimental view limitations, flow details and surface temperature data on the blade pressure side cannot be acquired. Additionally, the surface temperature imaged by IR camera is only for the coating, not the blade alloy substrate, making it impossible to quantify the influence of the coating' s thermal performance. For this reason, numerical simulation is implemented. The simulation object is one actual turbine blade tested in the experiment with its surface covered by a thin coating layer.

To characterize the real cooling performance of the cooled blade, it is necessary to consider solid heat conduction effects. Thus, a conjugate heat transfer numerical method is adopted. Meanwhile, property parameters of main gas flow, air, blade, and coating materials under experimental conditions are predefined, as shown in Tables 1 -4 . Gas and air are both treated as ideal gas for atmospheric environment. In addition, since gas temperature reaches 733K, radiation influence must be considered [15,23] for accuracy. The Rosseland radiation model is selected in the computation. Coating in the numerical model is treated as a thin layer material of 0.3mm uniform thickness, consistent with the mean thickness of actual coating on the external blade surface, and this thin layer is assigned similar physical properties to the actual blade coating for calculation.

ANSYS-CFX 14.5 software based on the finite volume method and fully implicit format is used to solve three-dimensional steady N-S equations and solid heat conduction equation. The k- SST turbulence model is adopted for its strength in solving CHT problems, and convergence criteria require each residual term to decrease until 10 . Due to cascade periodicity, this study only simulated one blade, and the computational domain with boundaries is shown in Fig. 4 [Figure 4: see original paper].

The blade structure with latticework cooling channels is highly complex, so both fluid and solid zones are meshed with unstructured grids. Specifically, five-layer boundary layer grids are added in the fluid near-wall region, with a total of 14 million cells after grid independence validation. Grid nodes on the fluid-solid interface are in one-to-one correspondence. Fig. 5 [Figure 5: see original paper] shows typical mesh in the mid-span section. Calculation working conditions agree with experiments, i.e., with mass flow ratio ω varying from 0.016 to 0.036, cooling performance on blade substrate surface and coating surface are investigated separately.

Results and Discussion

Validation of the Numerical Model

Before analysis and discussion, simulation results require verification. At the designed working condition (mass flow ratio $\omega = 0.026$, temperature ratio $\lambda = 0.53$) in this experiment, the infrared camera successfully captured infrared temperature fields of front and rear regions on the suction surface, shown in Fig. 6 [Figure 6: see original paper]. Fig. 7a [Figure 7: see original paper] presents cooling efficiency distribution on the suction side surface, analyzed after real surface temperature was translated from IR temperature using calibration correlation. Fig. 7b [Figure 7: see original paper] shows numerical simulation results at the same working condition.

It can be seen from Fig. 7 [Figure 7: see original paper] that numerical results of cooling efficiency distribution characteristics on the suction surface are similar to experimental results. Additionally, inflow stagnation occurs at the leading edge region of the blade, where corresponding cooling efficiency is lowest. Cooling air enters the blade internal channel from the blade root at the lowest temperature, and in the initial process of passing through the channel, heat begins to transfer from the internal blade wall to the coolant. Thus, maximum cooling efficiency in the front area of the suction surface occurs in this region. With further heat exchange between cooling air and blade, coolant temperature increases continuously, resulting in rapidly decreasing air cooling performance. Therefore, cooling efficiency in the suction surface front region shows an obvious decreasing trend along the spanwise direction.

Cooling efficiency in the overall rear region of the blade suction surface is improved compared with the front area. This is because the gas mainstream expands in the cascade flow path, leading to temperature decrease, which ultimately reduces heat flux from hot gas into the coating external surface. The optimum cooling efficiency on the suction rear surface occurs in the mid-chord region close to the root. However, the location of best cooling protection differs between numerical and experimental results. Numerical calculations predict that the highest cooling efficiency area is closer to the root than in the experiment.

Area-averaged cooling efficiency in front and rear regions on the suction surface obtained from experiment and numerical calculation is shown in Fig. 8 [Figure 8: see original paper]. It can be seen that for the rear part of the blade suction surface, numerical simulation shows good agreement with experimental results, with only slight bias at larger mass flow ratios. For the front part, the simulation seems to overestimate cooling efficiency but maintains the same trend as the experiment. The major reason for numerical prediction error lies in the complex geometry of model structure and flow structure, which are difficult to accurately simulate, as well as some hypotheses in numerical simulation. For example, numerical simulation assumes uniform thickness and roughness of blade coating, while for realistic cases, coating roughness is not uniform due to deposition, erosion, and spallation. Nevertheless, trends of mass flow ratio influence on area-averaged cooling efficiency are consistent for both simulation and experiment. Combined with cooling efficiency distribution comparison in Fig. 7 [Figure 7: see original paper], it is shown that this numerical model can predict cooling efficiency characteristics of the blade, and the effect of mass flow ratio on cooling efficiency can be accurately estimated. Thus, numerical results are credible to some extent.

Analysis of Cooling Performance

Fig. 9 [Figure 9: see original paper] presents cooling efficiency distribution on coating surface and substrate surface for both pressure side and suction side. It shows that the thermal barrier effect of the coating is very apparent, as cooling performance of the substrate surface is significantly better than that of the coating surface. There is a high cooling efficiency region on the coating pressure surface near the blade root, and cooling efficiency distribution characteristics are similar to those on the corresponding substrate pressure surface, meaning internal heat conduction through the coating does not change general cooling efficiency distribution features on the pressure side. Nevertheless, for the suction side, there are some differences. Overall, two high cooling efficiency areas are identifiable on both coating and substrate surfaces: one near the leading edge and the other located at the mid-chord zone. The area near the mid-chord of the suction surface is obviously larger, while maximum cooling efficiency is lower. Furthermore, the high cooling efficiency area on the substrate surface near the leading edge is larger than that on the coating surface. This comparison reveals that thermal barrier coating has significant influence on cooling efficiency distribution characteristics on the blade suction surface.

Fig. 10 [Figure 10: see original paper] depicts cooling efficiency distribution at the mid-span section of the solid domain, where the normal direction of cooling efficiency isolines represents heat transfer direction. The denser the isolines, the greater the heat transfer rate. It is concluded that cooling efficiency isolines in the leading edge area are almost parallel to the blade contour and relatively dense, indicating a large amount of heat flux occurring here due to the large temperature difference between inside and outside of the blade wall in this region. Heat conduction through the blade solid wall is mainly one-dimensional within the solid blade alloy part. Cooling efficiency isolines near the trailing edge area tend to be perpendicular to the blade contour. This may be caused by the lack of effective cooling structure near the trailing edge, leading to poor cooling performance. Heat transfer between inner and outer surfaces of the blade is weak in this region, while heat flux flows toward the blade trailing edge tip.

Moreover, it can be clearly observed from Fig. 10 [Figure 10: see original paper] that on both blade suction and pressure surfaces, locations of cooling efficiency peaks correspond to the front cooling chamber near the leading edge area. Cooling air enters the blade from the front cooling chamber at relatively low temperature, leading to relatively better cooling potential. While facing incoming stagnation flow with extremely high total temperature, it is impossible to achieve high cooling efficiency at the leading edge region. Thus, high cooling efficiency zones locate just downstream of the leading edge area on both suction and pressure surfaces. At the location of the cooling chamber far downstream on the blade suction surface, there is another high cooling efficiency region, whose formation mechanism will be analyzed by combining flow field characteristics.

Fig. 11 [Figure 11: see original paper] demonstrates streamline and velocity magnitude distribution at the mid-span section of the blade. It clearly shows that main flow attaches well to the blade surface contour, with no flow separation on either side. The mainstream undergoes accelerating expansion when passing along the cascade path, reaching maximum velocity at the throat location. After a short diffusion process, flow speed decreases. Temperature contour maps are presented in Fig. 12 [Figure 12: see original paper] corresponding to aerodynamic characteristics. As mentioned, mainstream flow into the cascade passage experiences accelerating expansion, resulting in gradual fluid temperature decrease. Accordingly, main stream temperature reaches its minimum value at the cascade throat region. This region is exactly where high cooling efficiency occurs at the rear part of the suction surface. Although cooling air has reduced cooling capacity after heat exchange with the hot blade metal, main stream temperature in this region decreases significantly. Therefore, another high cooling efficiency area appears at the throat location on the suction side.

Fig. 13 [Figure 13: see original paper] and Fig. 14 [Figure 14: see original paper] show cooling efficiency on coating and substrate (alloy) surfaces at mid-span section along normalized arc length separately. It indicates that variation of cooling air amount does not change cooling efficiency distribution characteristics on coating and substrate surfaces. As cooling air amount increases, cooling efficiency obviously enhances.

Three-dimensional heat conduction effects in the coating layer cause slight differences in cooling efficiency distribution between substrate and coating surfaces. For substrate surface under mass flow ratio $\omega = 0.026$, maximum cooling efficiency on suction side and pressure side at mid-span section are 60.7% and 37.9%, respectively, which are higher than those for coating surface. Coating enhancement is poorest at the trailing edge with only 1.8% improvement. The reason may be that formation of the maximum cooling efficiency area on the pressure surface is caused by the strongest internal cooling effect in this region, and heat load on the blade can be efficiently removed by internally flowing cooling air. In this way, the thermal barrier effect of the coating material' s low thermal conductivity is very significant. On the other hand, maximum cooling efficiency on the suction surface is generated due to decreasing temperature of externally flowing gas in this region, and its internal convective cooling performance is poorer than at maximum cooling efficiency locations on the pressure surface. Thus, the thermal barrier effect of the coating weakens at this position. The trailing edge lacks effective cooling protection, so its cooling efficiency is poorest and heat loaded on the blade alloy is difficult to remove by cooling air.

Superalloy blade constructs heat balance with the coating layer, so the thermal barrier effect of the coating is seriously weakened.

Variations of area-averaged cooling efficiency with mass flow ratio on pressure and suction sides of both substrate and coating surfaces are shown in Fig. 15 [Figure 15: see original paper]. When mass flow ratio increases from 0.016 to 0.036, area-averaged cooling efficiencies of substrate pressure surface, substrate suction surface, coating pressure surface, and coating suction surface increase by 52.3%, 43.4%, 48.7%, and 32.9%, respectively. Due to complex internal cooling and external fluid flow combination effects, thermal barrier impact of the coating on pressure and suction surfaces varies. Under designed mass flow ratio condition, cooling efficiency on the pressure side varies by 0.13 between coating surface and metal surface, while this value is 0.09 on the suction side.

Fig. 16 [Figure 16: see original paper] and Fig. 17 [Figure 17: see original paper] illustrate cooling efficiency on coating surface and substrate surface at mid-span section for varied coating thickness (δ) in the range of 0–0.45 mm. Results indicate that with increasing coating thickness, cooling efficiency on the coating surface decreases while corresponding cooling efficiency on the substrate surface increases gradually. However, enhancement or reduction of cooling efficiency varies at different mid-span section locations on substrate and coating surfaces. On the coating surface, cooling efficiency reductions of 0.010 and 0.001 occur at the leading edge and trailing edge, respectively. Additionally, maximum cooling efficiency on the suction side decreases by 0.006, and by 0.025 on the pressure side. On the substrate surface, cooling efficiency at these four locations shows enhancements of 0.052, 0.007, 0.038, and 0.047. Thus, it can be concluded that thermal barrier coating provides best thermal protection at the leading edge area, while worst at the trailing edge area.

Conclusions

The leading edge and trailing edge are the two main regions where poorest cooling performance occurs. For the leading edge area, cooling efficiency is mainly influenced by mainstream total temperature, making blade temperature somewhat higher. Even if internal convective cooling is intense, cooling performance on the outer surface in the leading edge region is not ideal. Cooling efficiency in the trailing edge region is low due to lack of high-performance cooling structures.

Due to accelerating expansion of main flow in the cascade path, there is a low-temperature zone near the cascade throat location. Correspondingly, there is a high cooling efficiency region on the suction side at this location.

The thermal barrier effect of the coating layer with the same thickness varies significantly at different locations. In areas with good internal cooling effectiveness inside the blade, the thermal barrier effect of the coating is obvious, while in areas lacking effective cooling structures, such as the blade trailing edge area, the thermal barrier effect is weakened.

Coating can significantly improve area-averaged cooling efficiency on the blade substrate surface compared with the coating surface. However, its effect differs considerably between suction and pressure surfaces. Under designed mass flow ratio condition, cooling efficiency on the pressure surface varies by 0.13 between coating surface and metal surface, while this value is 0.09 on the suction side.

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Note: Figure translations are in progress. See original paper for figures.